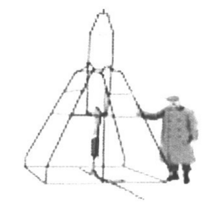

Spray Cooling And The Next Generation of NASA Space Flight

presented by

Eric Silk

Thermal Engineering Branch Code/545.0

NASA Goddard Space Flight Center

Greenbelt, MD 20771

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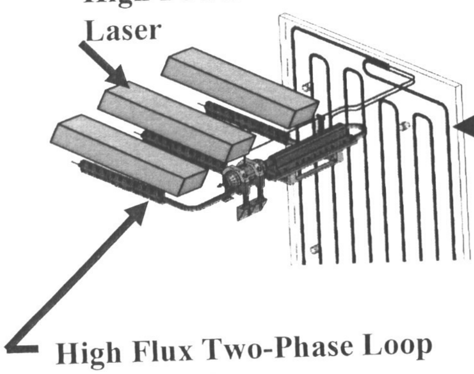
Thermal Control Subsystem for High Power Lasers



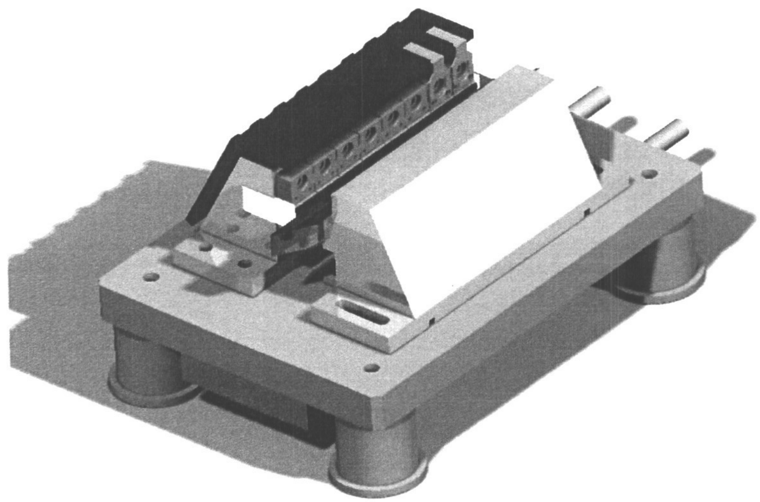
Key Area for Application

Technology Requirements:

- Demonstrate ability to remove high flux (>100 W/cm^2 heat flows in the 100's W range from advanced lasers while maintaining tight temperature control (approx. +/- 2 C)
- Demonstrate reliable startup and shut-down in a space environment
- Demonstrate both short and long term stability and temperature control

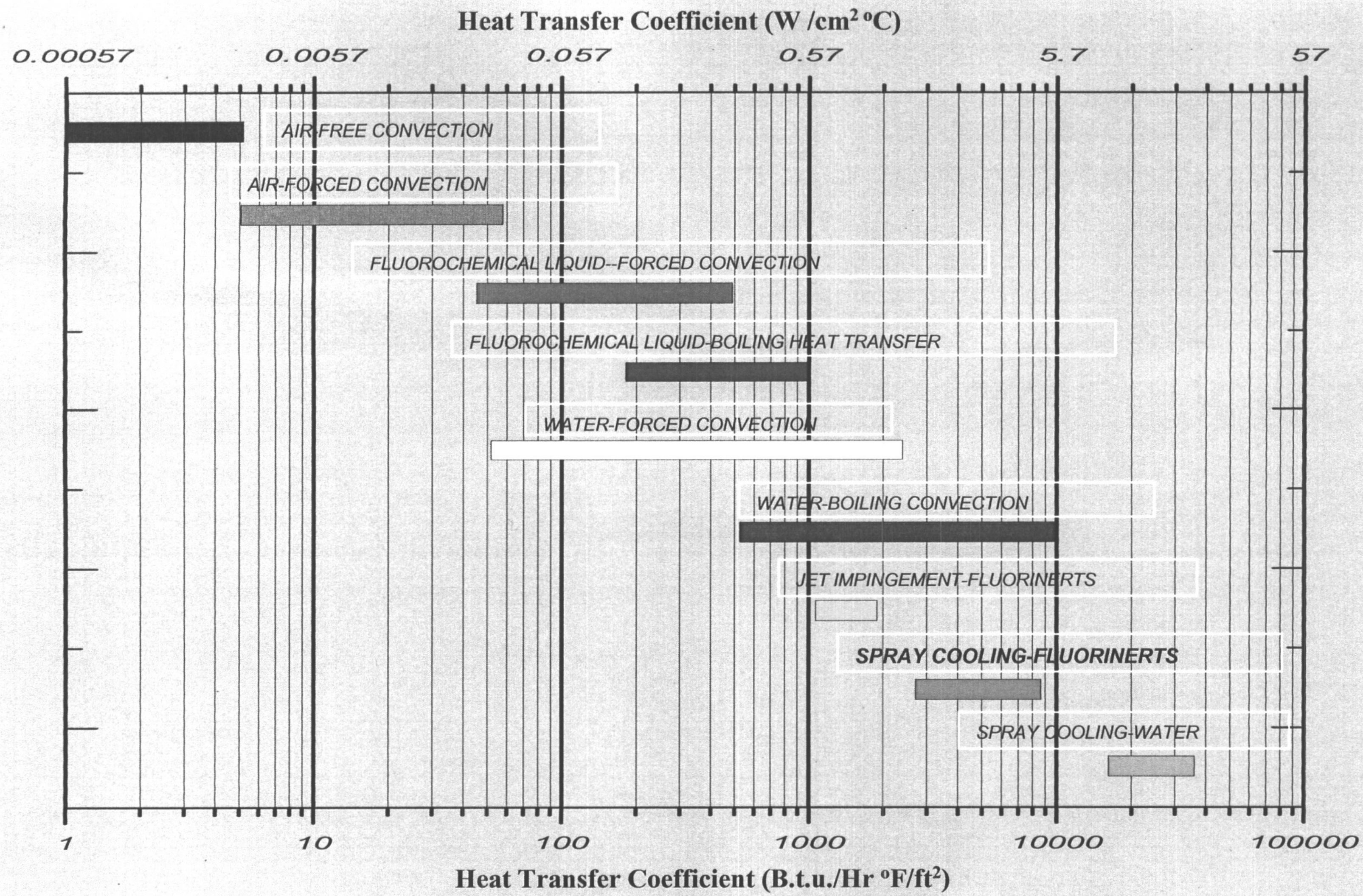
- **State of the Art:**

- High power lasers now use forced **convection** single-phase flow and/or simple conduction to remove heat. While this works in a laboratory environment, it is impractical for space applications due to vibration, parasitic pumping power requirements, and limitations on available on-board space.



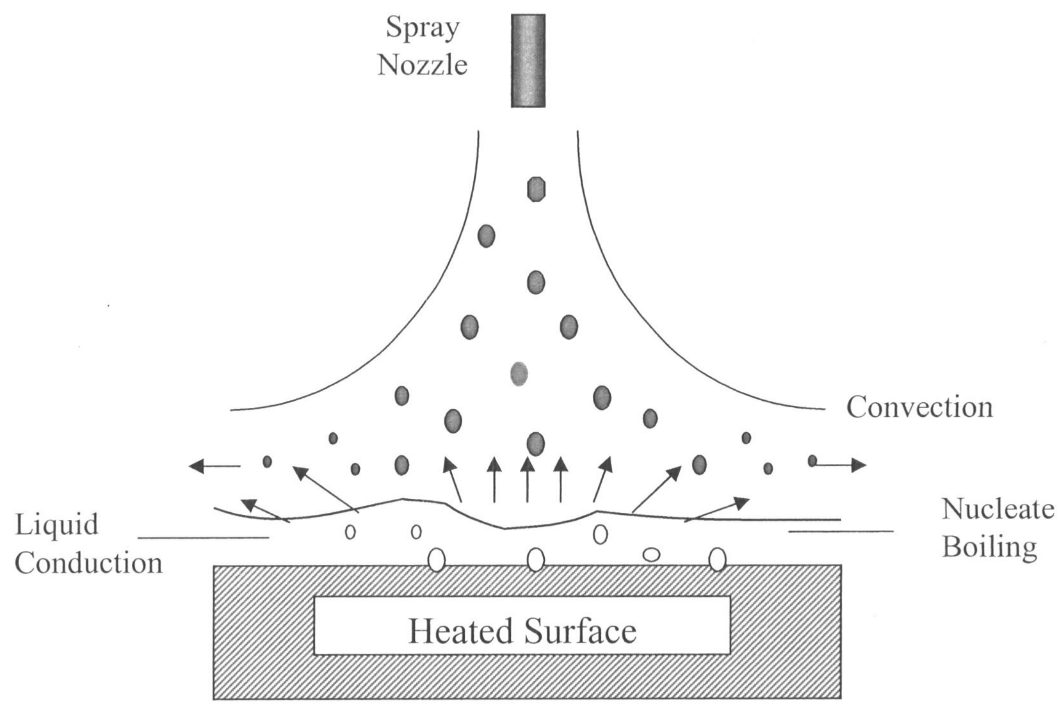
Laser Diode Array

Heat Transfer Rate Comparison

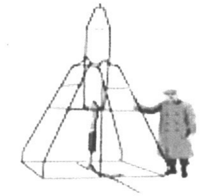


Spray Cooling Benefits

- High heat flux cooling capability (~100 W/cm^2 w/fluorinerts, >1000 W/cm^2 for water).
- Tight temperature control
- Applicable to lasers & high power density electronics.



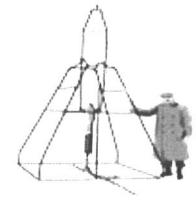
Diagram



Government Agencies Currently Pursuing Spray Cooling

- Air Force for Next Generation of Space Based Lasers (1 MW capacity)
- NASA for Next Generation Spaced Based Lasers (>1 kW capacity)
- Office of Naval Research for ship and submarine systems cooling (>1 kW capacity)
- Laboratory for Physical Sciences computer applications (100W – 1kW capacity)

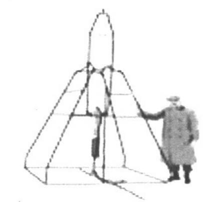
High Heat Flux Thermal Management Solutions are required!



High Heat Flux Thermal Management

Thermodynamic process considerations for Terrestrial and Extra-Terrestrial Applications

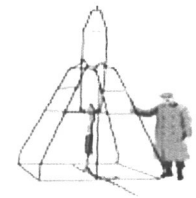
1) Heat acquisition from thermal controlled item.
2) Heat transport from absorption location to heat rejection location.
3) Heat rejection to ambient (mechanisms are important!)



Step 1: Spray Cooling Fundamental Investigations

- How do you maximize heat acquisition in a high heat flux thermal management system using spray cooling?
- Determine micro-gravity application thermophysics.
- Address spray cooling scalability issues.
- Performance testing using space applicable fluids

Spray Cooling Topics Investigated To Date



- Secondary Gas vs. Pressure Atomization (Yang et al., 1993)
- Mass flux of ejected fluid (Yang et al.,1993; Mudawar & Estes,1995)
- We & Re ($We=\frac{\rho U^2 d}{\sigma}$, $Re=\frac{\rho U d}{\mu}$) values (Healy et al., 1998; Mudawar & Estes, 1995)
- Spray Characteristics (Chen et al., 2002)
- Gravitational field effects (Kato et al., 1994;Yoshida et al., 2001;Yerkes et al., 2003)
- Dissolved gasses (Milke et al., 1997)
- Surface Roughness (Bernadin & Mudawar, 1999; Sehmbey et al.,1992 & 1995)

Enhanced Surface Pool Boiling Studies

Author	Surface	Fluid	Enhancement
Honda et al., 2002	Micro-pin finned/ submicron scale roughened combination surface	FC-72	heat fluxes 1.8 to 2.3 times greater than the corresponding flat surface
Rainey et al., 2001	Micro-porous surfaces with cavity features 0.1 to 1.0 μm	FC-72	heat transfer enhancements by a factor of 1.5 beyond that of the corresponding flat surface
Scurlock, 1995	Plasma sprayed surfaces with coating thicknesses of 0.13 mm to 1.32 mm	*R-12, LN2,* Argon, Oxygen	heat transfer enhancements 30 to 70 times that of the corresponding flat surface
Hsieh & Weng, 1997	Pitted coatings via sandblast technique	*R-134a, R407c*	increase in heat transfer coefficients by factors ranging 1.5 to 2.5
Chien & Webb, 1988	structured tunnels with pores (pores varied 0.1 mm to 0.23 mm)	*R-11, R-123*	heat transfer enhancement up to 30 times that of the corresponding flat surface

Enhanced Surface
Spray Cooling Concept

Enhanced surfaces subjected to pool boiling have been shown to enhance heat transfer beyond that of flat surfaces. The amount of the enhancement is dependent upon the enhanced surface used and its feature geometry.

Can enhanced surfaces (beyond the surface roughness range) result in enhancement of heat transfer with spray cooling?

<u>**Collaborators**</u>

Dr. Jungho Kim, University of Maryland

Dr. Ken Kiger, University of Maryland

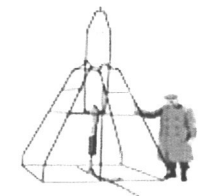
Enhanced Surface
Spray Cooling Concept

Can enhanced surfaces (larger than the surface roughness magnitude) result in enhancement of heat transfer with spray cooling?

If so, then:

1) How large is the heat flux enhancement?

2) What geometry yields the largest enhancement?



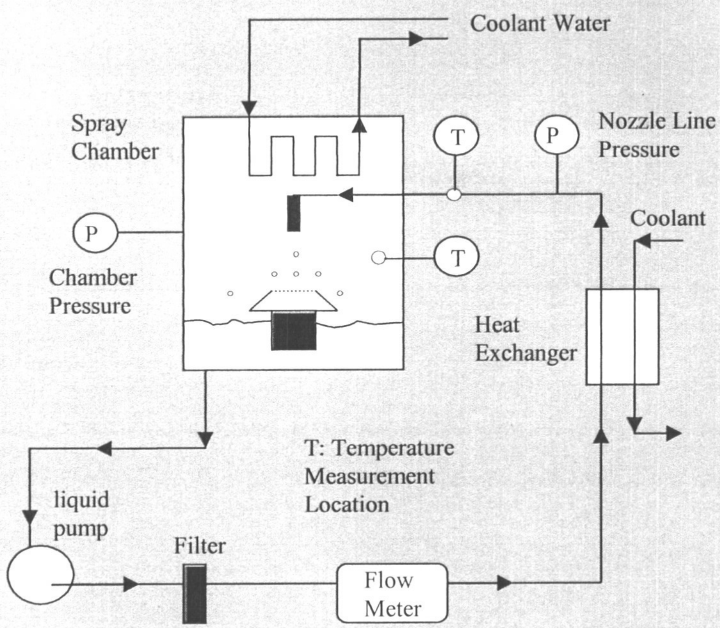
Enhanced Surface Spray Cooling

Fundamental Questions:

1) Placement of structures on a spray cooled surface can either hinder or enhance heat transfer by increasing nucleation site density and/or promoting flooding. How does surface geometry impact heat transfer?

2) What are the mechanisms by which surface geometry affects heat transfer? Does the heat transfer increase linearly with the wetted surface area (i.e. scalability)?

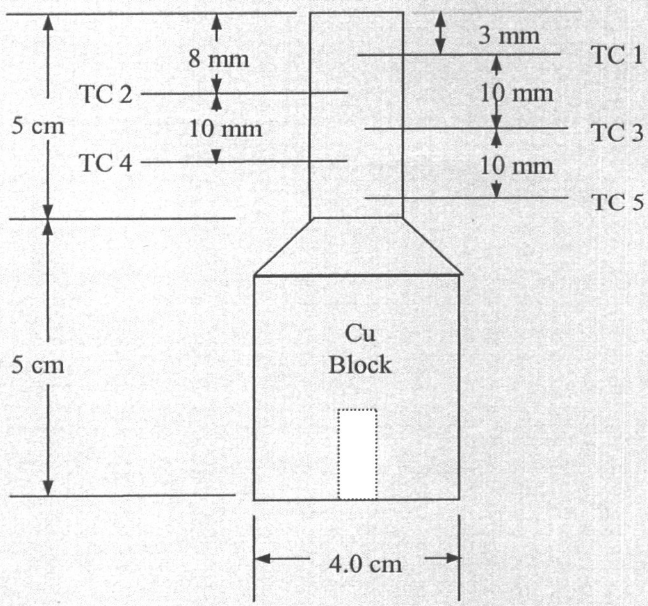
Goddard Test Rig Schematic



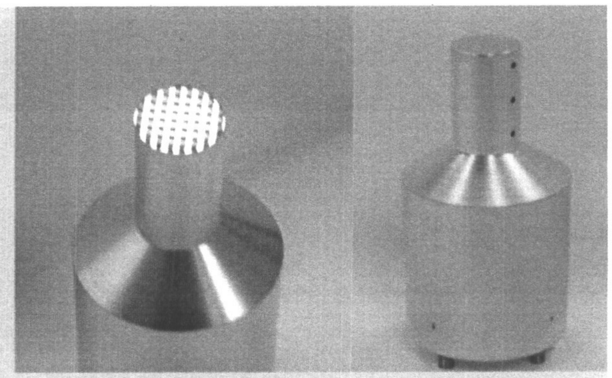
Spray Cooling Test Rig Configuration

- Stainless Steel test chamber (*height*=18", *diameter*=15")
- Four quartz windows around perimeter and on top cover plate for visualization
- OFHC test article (copper block, *k=389 W/m K*)
- 2x2 Parker Hannefin proprietary pressure atomizer
- 500 *W* cartridge heater

Goddard Test Rig Schematic

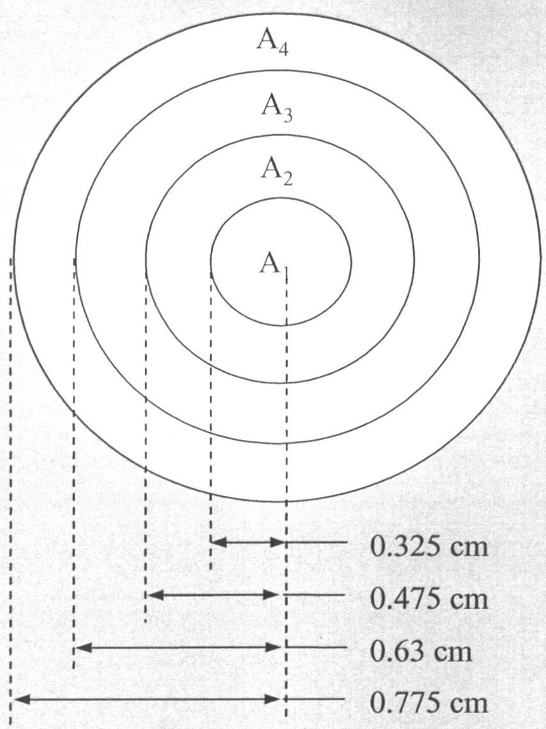


Copper block schematic with TC locations (not to scale)



- OFHC test article (copper block, k=*389* W/m K)
- 2.54 μm nickel undercoat/ 1.27 μm gold topcoat
- Heat exchange surface cross sectional area of 2 cm^2
- Five TC locations
- 500 W cartridge heater used

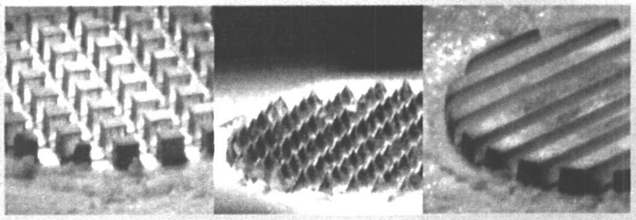
Nozzle Volume Flux



Section	Area (cm^2)	Area (%)	Vol. Flux (m^3/m^2 s)	Γ_i
A_1	0.33	17.5	0.026	2.0
A_2	0.38	20	0.024	1.8
A_3	0.54	28.5	0.007	0.6
A_4	0.64	34	0.005	0.4

Γ: local volume flux between concentric cylinders weighted by the total volume flux over the entire heater surface

Structured Surfaces

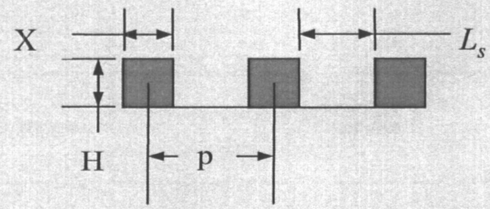


Cubic Pin Fins *Pyramids* *Straight Fins*

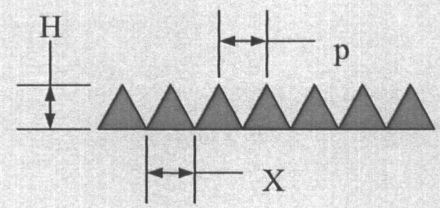
Surface	p (mm)	X (mm)	L_s (mm)	H (mm)	A_s (cm^2)
Cubic Pin Fins	2	1	1	1	4.0
Straight Fins	2	1	1	1	4.0
Pyramids	1	1	0	1	4.5

- p is the pitch
- X is either thickness, side length, or diameter
- L_s is the distance between successive structures
- A_s is the total surface area

$$p = X + L_s$$



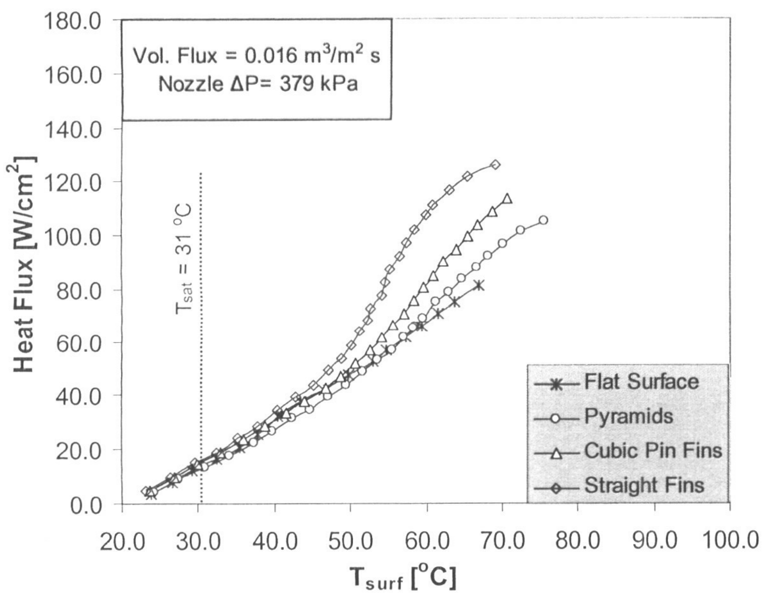
Cross Sectional View for Cubic Pin Fins and Uniform Cross Sectional Rectangles



Cross Sectional View for Pyramids

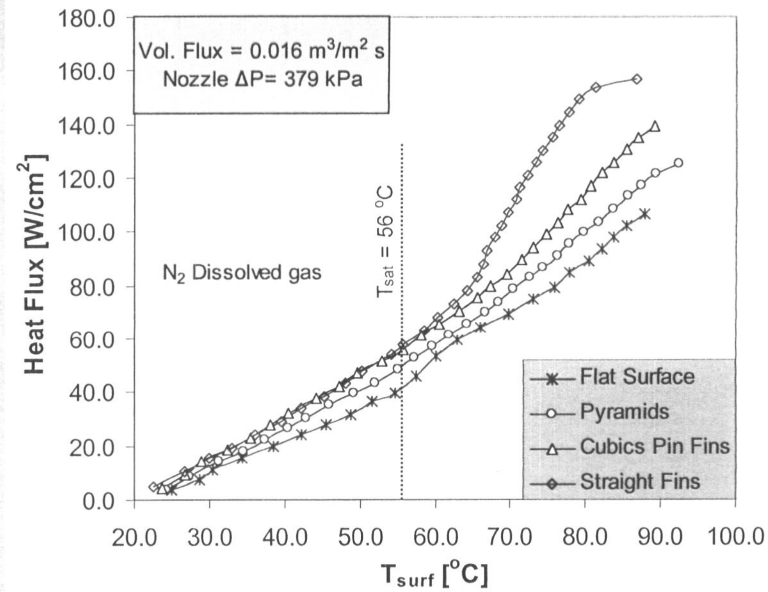
Gassy & Degassed Results

Degassed

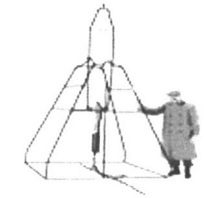


- Chamber pressure at 41.4 kPa
- Maximum heat flux for the Straight Fin surface was 126 W/cm^2
- Heat flux enhancement of 55% (relative to Flat surface) when using straight fins.

Gassy



- Chamber pressure of 101 kPa w/GN$_2$ backfill
- Maximum heat flux for the Straight Fin surface was 156 W/cm^2
- Heat flux enhancement of 47% (relative to Flat surface) when using straight fins.



Results Continued

Degassed Case

Parameter	Flat	Cubic Pin Fins	Straight Fins	Pyramids
A_s (cm^2)	2.0	4.0	4.0	4.5
q''_{max} (W/cm^2)	81	114	126	105
T_{max} (^{o}C)	67.1	70.6	69.1	75.6
η_{max}	30	43	47	39

Gassy Case

Parameter	Flat	Cubic Fins	Straight Fins	Pyramids
A_s (cm^2)	2.0	4.0	4.0	4.5
q''_{max} (W/cm^2)	106	139	156	125
T_{max} (^{o}C)	87.7	89.1	86.7	92.3
η_{max}	36	47	53	43

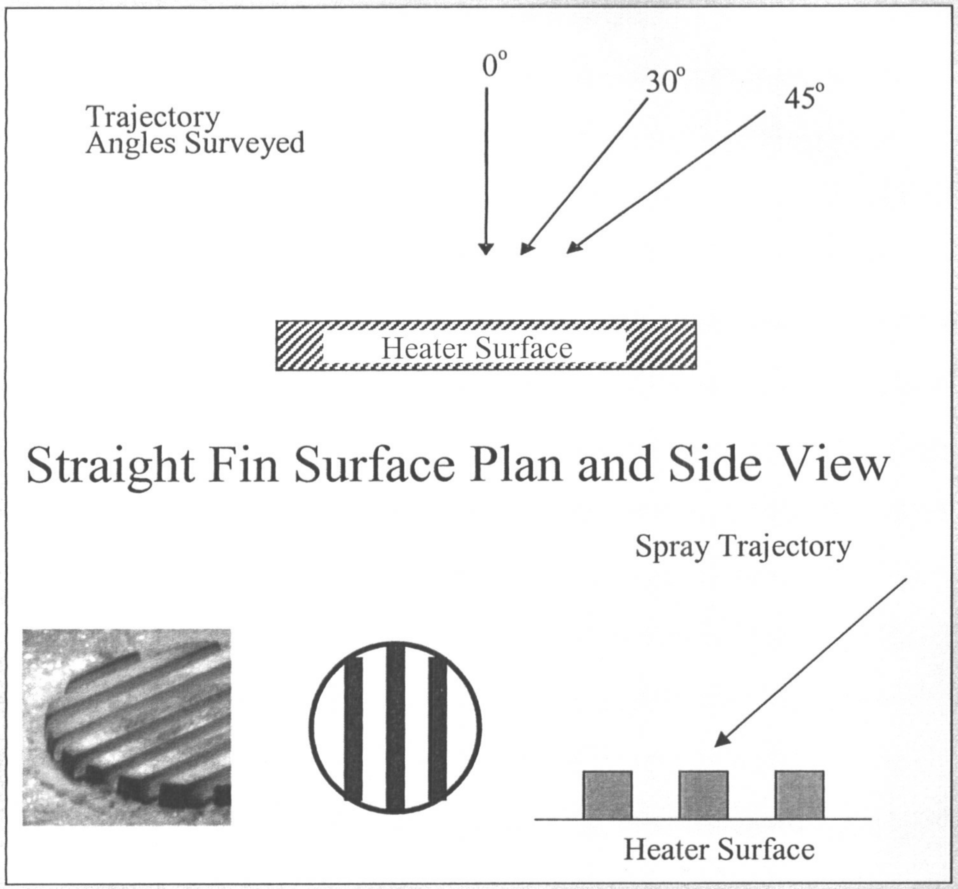
$$n_{\max} = \frac{q_{\max}}{\rho_l \dot{V}_{eff}\left[c_p\left(T_{sat} - T_l\right) + h_{fg}\right]}$$

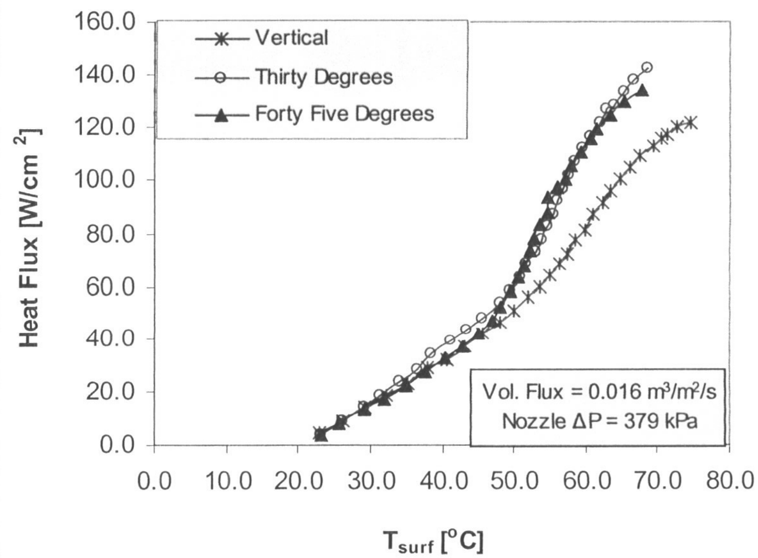
- Heat transfer does not scale with surface area for structures tested!
- Increase in spray cooling evaporation efficiencies for each of the enhanced surfaces. Implies structured surfaces fostered increase in multi-phase heat (2-Φ) transfer effects.

Surface Structure Study Conclusions

- Enhanced surfaces (cubic pin fins, straight fins, pyramids) beyond the surface roughness level displayed an increase in heat transfer.
- Surface temperatures at CHF for each of the cases showed small increase (≤ 8 °C)
- Dissolved gasses promoted heat transfer for each of the enhanced surfaces.
- Heat flux does not scale with the total surface area or the base area of the surface (non-comparative structure geometries).
- Structures impact heat flux via fluid management on the surface (e.g. Cubic pin fins vs. Straight fins)
- Total surface efficiencies for enhanced surfaces very low ($< 30\%$). This suggests 1-Φ convection is dominant enhancement mechanism. However further investigation required.

Angular Trajectory Studies





- Chamber pressure at 41.4 kPa
- Maximum heat flux for the Straight Fin surface at 30° from the vertical was 138 W/cm^2
- Heat flux enhancement of 63% (relative to Flat surface) when using straight fins with angular trajectory.

AFRL/GRC Joint Work

Micro-gravity Flight Experiment

Air Force Research Laboratory

Dr. Kirk Yerkes

+

Glenn Research Center

Eric Golliher

Dr. John McQuillen

Goddard Space Flight Center

Eric Silk

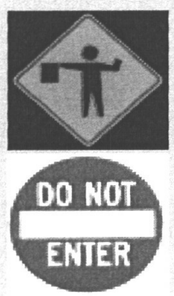
Scalability Studies / Space Compatible Fluids

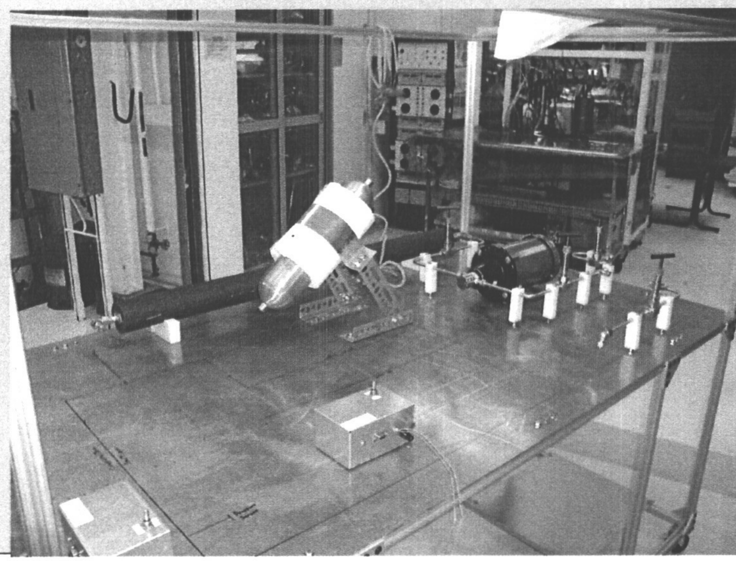
Features
- Ammonia Compatible
- 2kW capacity
- Large Area Scalable

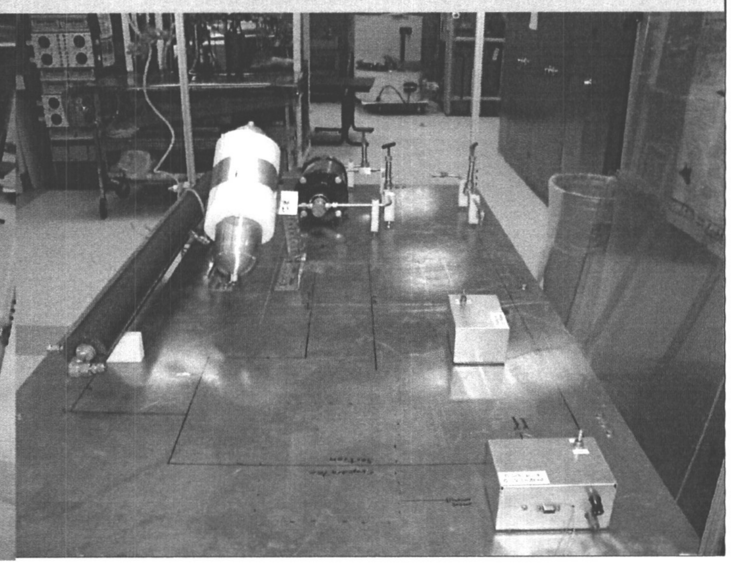
Completion Date
Spring 2005

Proof of Concept Testing
Summer 2005

Under Construction

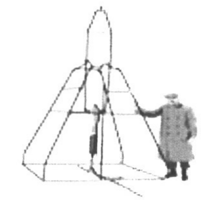






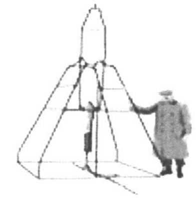
Future Work

- Continuation of experiments using enhanced surface copper block selections (cubic pin fins & straight fins).
- Continuation of Angular Spray Trajectory Studies using straight fins
- Development of quantitative heat flux relations for cubic pin fin and straight fin surfaces
- Investigation of specialty enhanced surfaces
- Initiate large scale area spray cooling investigations
- Micro-gravity spray cooling with enhanced surfaces



Step 2: Heat Transport To Rejection Location

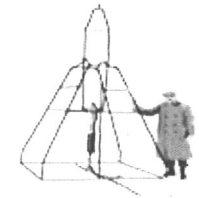
- Pumps vs. Compressors
- Hot and Cold sink temperature regimes
- Fluid Compatibility



Pump vs. Compressor Overview

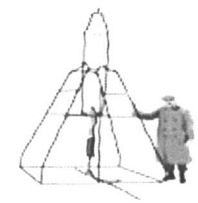
Liquid Pumps	Vapor Compressors
1-Φ operation	Sump line vapor quality requirement
Sump line liquid quality requirement	Fluid compatibility for internal components
Fluid compatibility for wetted components	On demand start-up
On demand start-up	Compression ratio
Lifetime wear	Temperature Lift
	Lifetime wear

Operating Temperature Regimes and Fluid Compatibility



The working fluid must undergo evaporation and condensation within the operating ranges of the object being cooled and the cold sink of space.

Terrestrial Spray Cooling Fluids	Traditional Space Compatible Fluids
Fluorinerts (FC-72, FC-87, etc.)	Ammonia
H_2O	Neon
Methanol	Nitrogen
Nitrogen	Ethane
R-134a	Methane
Ammonia*	Methanol



Step 3: Heat Rejection To Ambient

- Heat Transfer Mechanism

In a space environment, the heat transfer mechanism to ambient is limited to radiation.

$$q'' = \sigma F_{i,amb}\left(T_i^4 - T_{amb}^4\right)$$

The rejection heat flux is driven by the 4th order temperature difference between the radiator and the sink.

Code T Initiative and Spray Cooling

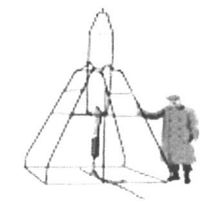
Temperature Range	Low Heat Flux (< 50 W/cm^2)	Intermediate Heat Flux (50 – 100 W/cm^2)	High Heat Flux (> 100 W/cm^2)
Low Temperatures (< 150K)	LHPs, Spray Cooling	LHPs, Spray Cooling	Spray Cooling?
Room Temperature (150K - 400K)	LHPs, CPLs, Vapor Compression, 1-Φ convection, Spray Cooling	LHPs, CPLs, Vapor Compression, 1-Φ convection, Spray Cooling	Spray Cooling?
High Temperature (> 400K)	Spray Cooling?	Spray Cooling?	Spray Cooling?

Traditional Operating Ranges

Exploration Systems Mission Directorate (ESMD) Temperature Operating Ranges

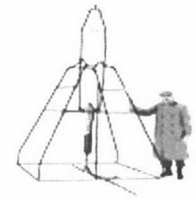
High Temperature Considerations

- Viable working fluids for high temperature evaporation and condensation cycle. (i.e. liquid metals such as Cesium, Sodium, Potassium and Lithium).
- Construction materials for pumped fluid loop and prime mover
- Radiator sizing (for high heat flux applications)



Conclusions

Given the targeted heat flux and temperature operating regimes, spray cooling appears to be a viable option for thermal management of the new ESMD programs. However, further technology development is required.



Acknowledgements

Special Thanks to the NASA Goddard Space Flight Center Laser Risk Reduction Program for their continued support in this development effort.